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High Frame Rates and the Visibility of Motion Artifacts

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***Abstract*.** Video frame rates, higher than those in conventional use today, have been shown to lead to an increase in perceived quality due to a reduction in the visibility of motion artifacts, specifically motion blur and temporal aliasing. Despite this, frame rates used in television and cinema have remained constant for many years. Although not currently in widespread use, the most recent UHDTV video standard (Rec. 2020) specifies higher spatial resolutions and a wider dynamic range than its predecessor; it also supports frame rates up to 120 Hz. In this context, we investigate here the influence of temporal sampling rate on the visibility of aliasing artifacts. Our results show that impairments in motion quality can be tolerated to a degree, and that it is acceptable to sample at frame rates 50% lower than the critical frame rate required to completely eliminate perceptible motion artifacts. Based on real world data related to median viewing distances and screen sizes, we make the recommendation that frame rates should be at least 100 Hz in future immersive video formats. Two further experiments show how the critical frame rate is dependent on both stimulus size and luminance. With respect to luminance dependence, our results indicate that the critical frame rate for a bright high-dynamic range display may be 30% higher than that for a conventional low-dynamic range display.

Keywords. *High frame rates, motion artifacts, motion quality, high dynamic range, UHDTV*

Introduction

As the demand for higher quality video experiences increases, the pressure to extend the video parameter space beyond current spatial and temporal resolutions, dynamic ranges and screen sizes becomes ever greater[1]. The benefits of extending the video parameter space have been recognised in the latest UHDTV (ultra-high-definition) video standard, ITU-R Recommendation BT.2020-2[2], which specifies increased bit depths, a wider colour gamut, increased spatial resolution (up to 7680 x 4320) and frame rates up to 120 Hz.

Despite other advances, the frame rates used in television and cinema have remained constant for many years, not exceeding 60 Hz. There is, however, a clear relationship between frame rate and perceived quality[3,4,5]. Increased frame rates lead to a more accurate representation of motion through a reduction in motion blur and temporal aliasing artifacts such as strobing[6,7].This is particularly important for large screen sizes and for reduced viewing distances. High frame rates have stimulated interest in the film and broadcast communities[8], and also in virtual reality (VR), where headset technology is a primary driver for increased frame rates due to the high speed motion imposed by head movements[9].

Frame rate recommendations for future video formats must take the visibility of both motion blur and temporal aliasing artifacts into account, since these are interdependent[10]. Results that characterise the perceptibility of motion blur over a range of frequencies have existed for some time[11], yet there are few reports which similarly quantify the visibility of temporal aliasing artifacts over the visible range[6,12]. We address this in our experiments by using a strobe light with a controllable flash frequency to simulate the video capture process. A model for the critical frame rate at which temporal aliasing artifacts becomes perceptible has been developed theoretically by Watson et al.[13], who show that the critical frame rate increases linearly as the speed of the stimulus increases. This suggests that higher frame rates will be needed for the larger screen sizes associated with the latest UHDTV video standard[2], as the speed of the stimulus subtended on the retina will be greater for similar viewing distances.

A number of other factors may also influence the visibility of temporal aliasing artifacts, such as stimulus type, stimulus contrast, viewing conditions and eye movements[12]. However, in this paper we focus on the effects of stimulus size and luminance, as these are the key factors in the context of UHDTV formats (higher spatial resolutions can faithfully reproduce smaller objects) and higher dynamic range displays.

This paper describes a method for assessing critical and acceptable frame rates. We present experimental data showing that aliasing is visible at frame rates up to 600 Hz, well beyond what is currently feasible given current display technology.

The primary contributions of this work are:

i. An assessment of critical and acceptable frame rates for various stimulus speeds

ii. Quantification of the relationship between display luminance and critical frame rate

iii. Recommendations of acceptable frame rates for future video formats

Related Work

The critical frame rate (CFR) at which motion artifacts such as motion blur or temporal aliasing become perceptible can be calculated using knowledge of the human visual system and sampling theory. Subjective experiments using video sequences on the other hand allow us to quantify the visibility and perceived quality of motion artifacts below the critical frame rate. Prior work in these areas is described below.

Critical Frame Rate: Motion Blur

Noland[10] calculated that a frame rate of 700 Hz is needed to keep motion blur at an imperceptible level, assuming Nyquist sampling with an anti-alias filter (i.e. with no temporal aliasing). The closest approximation to this in a real camera is a shutter that is fully open over the entire frame period. This filters by integrating the light over time, introducing blur.

If the camera shutter duration (sometimes called shutter angle) is set to be very short, impulsive sampling with no anti-alias filter is approximated. Motion blur is then reduced, but at the expense of increased temporal aliasing. In order to make a practical frame rate recommendation, it is therefore important to understand the visual impact of aliasing artifacts.

Critical Frame Rate: Temporal Aliasing

The spatio-temporal contrast sensitivity function (CSF)[14] is widely used to model the frequency response of the human visual system (HVS). Watson et al.[13] define a threshold on the contrast sensitivity function, referred to as the 'window of visibility', which delineates the region of perceptible spatio-temporal frequencies. The size and shape of the window of visibility is affected by a number of factors, such as: eye movements, luminance, filtering by the display and the camera, and the speed of the stimulus[15,16].

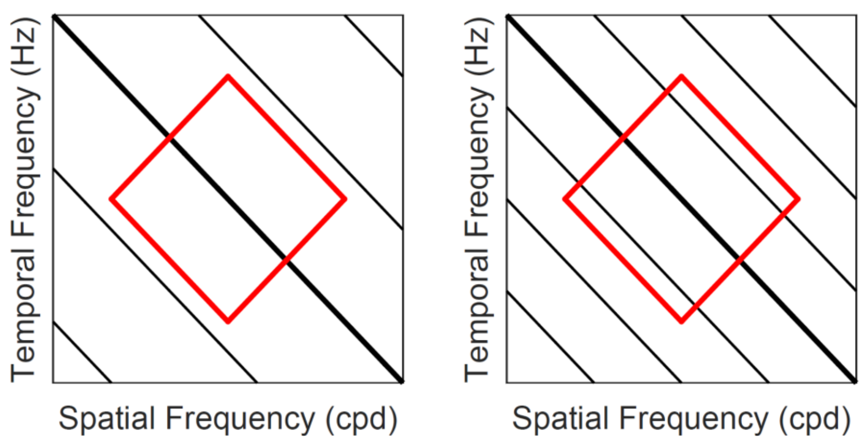


Figure 1. Spatio-temporal frequency spectrum of a temporally sampled line moving at a constant speed (thick black line), and its spectral replicas (thin black lines), falling (left) outside and (right) inside the window of visibility.

Spectral replicas of the original signal are generated through the process of temporal sampling[17]. Figure 1 shows the spectral replicas of a line moving at constant speed. The temporal separation between the replicas is equal to the frame rate[15] and therefore, at a certain frame rate (if no anti-alias filter is present), spectral replicas will fall inside the window of visibility and thus become perceptible. An example of this can be seen in Figure 1 (right). If a spectral replica enters the window of visibility at the vertex corresponding to high temporal and low spatial frequency (where the flashes of individual frames become visible), we will perceive flicker, whereas if a spectral replica enters at the vertex corresponding to high spatial and low temporal frequency (when a high speed stimulus moves beyond its own extent between frames), we will perceive strobing[15].

Flicker is usually defined as unwanted fluctuations of luminance and/or chrominance, and can be eliminated by sampling at the temporal acuity limit of the human visual system. The flicker associated with impulse displays (e.g. CRTs) is supressed when using a hold-type display, or by using frame-insertion techniques. Other forms of flicker such as quantisation flicker are introduced during compression, which is beyond the scope of this study.

Strobing can be perceived in a variety of ways, such as multiple imaging, non-smooth motion and edge flicker[18]. Multiple imaging (sometimes called banding), occurs when multiple, spatially separated versions of the stimulus are visible simultaneously[19] (due to persistence of vision[20]). Non-smooth motion (judder) is exacerbated when a hold-type display is used. This was therefore only apparent in our experiments at the lower frame rates tested, as impulsive sampling was simulated with the use of a strobe light.

Figure 3 shows a moving line sampled by a strobe light with a very short duty cycle, in which multiple imaging can be observed. The displacement between the multiple images is equal to the distance travelled between samples in one frame period with a fixated gaze, therefore the multiple images will appear closer together as the frame rate increases. In some scenarios, the multiple images will overlap, and this can lead to the visibility of a number of artifacts such as spoking and smearing[7]. At a certain frame rate the spatial displacement between the multiple images will be imperceptible, and at this point, temporal aliasing in the form of strobing will be eliminated.

Critical Frame Rate: Model

Watson derived the frame rate at which temporal aliasing, in the form of both flicker and strobing, becomes imperceptible[15]:

$$f = \max(w_0, ru_0) \qquad (1)$$

where w_0 is the temporal acuity limit of the human visual system (Hz), sometimes referred to as the critical flicker frequency (CFF), r is the speed of the line subtended on the retina (˚/s) and u_0 is the spatial acuity limit of the human visual system in cycles per degree (cpd). Sampling above this frame rate ensures that spectral replicas of a moving line fall outside the window of visibility.

The critical frame rate predicted by the model is affected by a number of factors, including: luminance (which effects the size of the window of visibility[15]), the stimulus (size, spatial frequency, contrast etc.) and eye movements[21], since temporal aliasing artifacts are diminished when a stimulus is tracked (as r will decrease). However, smooth pursuit eye movements may lead to the perception of edge flicker and an increased perception of blur when using high-persistence displays (e.g. hold-type)[18]. In our experiments we minimise eye movements by requiring participants to fixate their gaze on a marker, as this will highlight temporal aliasing artifacts[12]. Laird et al.[22] have shown that subjects are able to satisfactorily fixate in this way. The critical frame rate model does not account for any spatio-temporal filtering performed by either the display or the camera shutter, and therefore provides an upper limit on the frame rate needed in practice.

Related Subjective Experiments

Subjective experiments run on actual video sequences can provide realistic frame rate recommendations, as they take into account the role of the camera and display. While these are important, they come at the cost of increased complexity, along with a substantial increase in the number of independent variables, which can make it difficult to make generalised predictions. They also limit the range of the variables tested due to technological limitations of current display hardware.

Previously reported subjective tests on video sequences have shown that an increase in frame rate can lead to an increase in perceived quality[3], at least up to 240 Hz[4], although this increase in quality shows diminishing returns and is content dependent[5]. Alongside an increase in overall quality, perceived impairment in motion quality due to strobing and motion blur is reduced with increased frame rates[7,23,24]. Kuroki et al.[6] propose a frame rate of 250 Hz to eliminate both motion blur and the temporal aliasing artifacts caused by strobing. These subjective experiments were, however, limited by the capabilities of the capture and display technology. In order to overcome this limitation, in our experiments we employed a stroboscopic display system, which allowed us to investigate a much wider range of frame rates, up to 2000 Hz.

Experimental Setup and Methodology

Overview

Figure 2. The white circular card attached to the tape machine, with the black lines used as the moving stimulus.

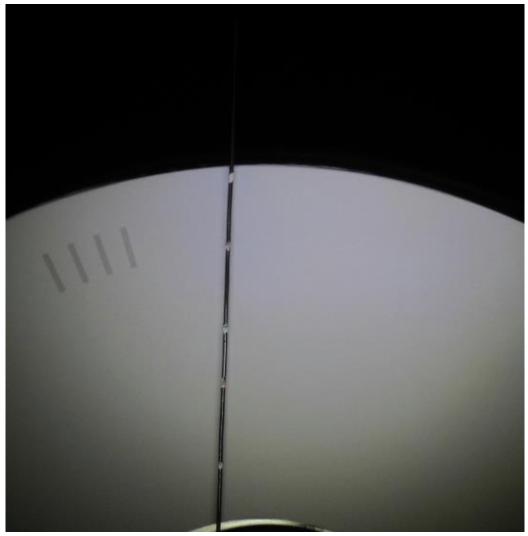


Figure 3. An example of a multiple imaging artifact, along with the vertical wire used for fixation.

A white circular rigid matte card (27 cm in diameter) with 1 cm long radial black lines was attached to the tape reel of a Studer A307 tape recorder (see Figure 2). The speed of the lines relative to the participant was adjusted by changing their radial position and/or the speed of rotation. The lines had a Weber contrast of -0.93 when illuminated for all test conditions.

A Monarch Instrument Nova-Strobe PBL strobe light was used to simulate temporal sampling at different frame (flash) rates. Luminance was controlled by changing the duty cycle of the strobe light. To ensure that impulsive sampling was simulated, and that the line did not appear to move during a flash, the duty cycle of the strobe was set such that the distance travelled by the line within a flash was always smaller than the spatial acuity of the human eye, which we assumed to be 1 arc min[25] (corresponding to a maximum flash duration of 238 µs at 70˚/s). Therefore no motion blur is imposed by the strobe light, although a blurring may occur in the human visual system[14]. To reduce the risk of photosensitive epilepsy, the lowest flash rate of the strobe was limited to 60 Hz[26].

Participants sat 60 cm away from the stimulus plane, while the strobe was placed 20 cm away, which gave an illuminated region of approximately 10˚ x 8.5˚. The strobe was the only source of light in the room. Participants fixated their gaze on a marker on a thin vertical wire in front of the card, which can be seen in Figure 3. Head movements were restricted by using a chin rest, while a small viewing window ensured that only the illuminated region was visible.

Experiment 1: The Visibility of Motion Artifacts and their Effect on Motion Quality

Here we quantify the visibility of temporal aliasing artifacts and their impact on motion quality below the critical frame rate.

The luminance of the strobe was set to 150 cd/m^2. However, due to limitations of the strobe light, some variation in measured luminance levels was observed with respect to flash rate, as shown in Table 1. The luminance of the stimulus (L_s) was approximately 10.5 cd/m^2 for all flash rates. Luminance levels were measured with a Konica Minolta CS-2000 spectroradiometer.

The stimulus, which is modelled as a square pulse, had a width (measured as the angle subtended on the retina) of 20 arc min, corresponding to 0.35 cm. The stimulus speeds used in the experiment were: 10, 30, 50 and 70˚/s.

Table 1. Measured Time-Averaged Luminance Levels (cd/m^2) for the Tested Flash Rates.

Flash Rate (Hz)	60	100	150	300	600	1000	2000
Luminance (cd/m^2)	158	154	151	149	151	145	168

The double-stimulus impairment scale (DSIS)[27] method was used to record subjective opinions, and involved participants being shown a reference flash rate for 5s before being shown a randomly chosen flash rate for a further 5s. Participants then rated their perceived impairment in motion quality compared to the reference. Participants also recorded whether they perceived blur, multiple imaging and/or non-smooth motion. Impairment was rated on a 5-point scale[27] ranging from ‘Imperceptible’ (5) to ‘Very annoying’ (1). The reference flash rate used to represent alias-free motion was chosen to be 2000 Hz (although aliasing was found not to be perceptible over 1000 Hz during informal experimentation for all test conditions, 2000 Hz was chosen to absolutely guarantee that aliasing was not visible at the reference flash rate), and was included as a test presentation.

Twenty-three participants from BBC Research & Development with an age range of 21-65 years took part in the experiment, and were screened for normal or corrected-to-normal vision. Prior to testing, each participant was given instructions related to the testing process, and took part in a brief training exercise, highlighting the motion artifacts they were likely to perceive. A complete session lasted no longer than 30 minutes, and contained regular breaks to limit fatigue. Participants' scores were screened in accordance with the method outlined in ITU-R BT. 500-13[27].

Experiment 2: The Effect of Stimulus Subtended Angle

This experiment investigated the relationship between stimulus subtended angle (size) and critical frame rate. The stimuli used in the experiment had subtended angles of: 20, 8.1, 3.3, 1.3, 0.5 arc min. The speed of the line was set to 70˚/s, which was the fastest speed possible given the experimental setup. The luminance of the strobe light was kept constant for all stimulus widths (W), and was set as close to 150 cd/m^2 as was possible (see Table 1).

The method of adjustment was used to determine critical frame rates, where the flash rate of the strobe was decreased in 50 Hz increments from a random starting point between 1000 Hz and 1500 Hz at a 50 Hz boundary. Once the participant reported a perceptible difference between adjacent flash rates (caused by the introduction of temporal aliasing), the experimenter recorded the average of the two adjacent flash rates, as the critical frame rate could lie anywhere between the two. This process was repeated 3 times for each test condition, and the mean frequency was calculated.

Other psychophysical methods such as the method of constant stimuli, staircase procedures and forced-choice methods were considered, with the view of generating more accurate psychometric functions for each participant. However, as the strobe light had to be controlled manually, these methods were deemed to be infeasible, as we wished to limit fatigue and inconvenience for participants. We mitigated the high margin of error often associated with the method of adjustment by using a fairly large number of participants.

Sixteen participants from BBC Research & Development, with an age range of 21-65 years took part in the experiments, after screening for normal or corrected-to-normal vision. Prior to testing, each participant was given instructions related to the testing process, and took part in a brief training exercise. A complete session lasted no longer than 30 minutes, and contained a 5 minute interval between the two experiments.

Experiment 3: The Effect of Luminance

By investigating the critical frame rate at which temporal aliasing becomes perceptible as a function of luminance, we can demonstrate how the visibility of temporal aliasing artifacts will be affected by the increased luminance levels likely to be employed in future high-dynamic range formats.

The luminance of the strobe light (altered by changing the duty cycle) reflected from white parts of the card (L_b) was set as close as was possible to the target luminance levels shown in Table 2. The luminance of the stimulus can be calculated from its Weber contrast (-0.93). The stimulus used in this experiment had a subtended angle of 20 arc min. The speed of the line was set to 70˚/s.

The methodology and participants were the same as for experiment 2; only that the luminance of the strobe was changed.

Table 2. A Selection of Measured Time-Averaged Luminance Levels.

Flash Rate (Hz)	Measured Luminance (cd/m^2)				
200	154	391	782	1612	3140
600	145	382	777	1609	3122
1000	134	372	769	1607	3083
Target Luminance (cd/m^2)	150	400	800	1600	3200

Results

Experiment 1

Mean impairment scores (MIS) collected in the experiment are shown in Figure 4. According to common practice[6,23], we interpret a mean impairment score of 4.5 as the critical frame rate, and 3.5 as the frame rate corresponding to an acceptable level of impairment. Critical and acceptable frame rates increase as the speed of the stimulus increases. Unacceptable impairment in motion quality due temporal aliasing was not observed at the lowest speed of 10˚/s. We see the effect of diminishing returns with respect to impairment, except when the stimulus speed is 70˚/s.

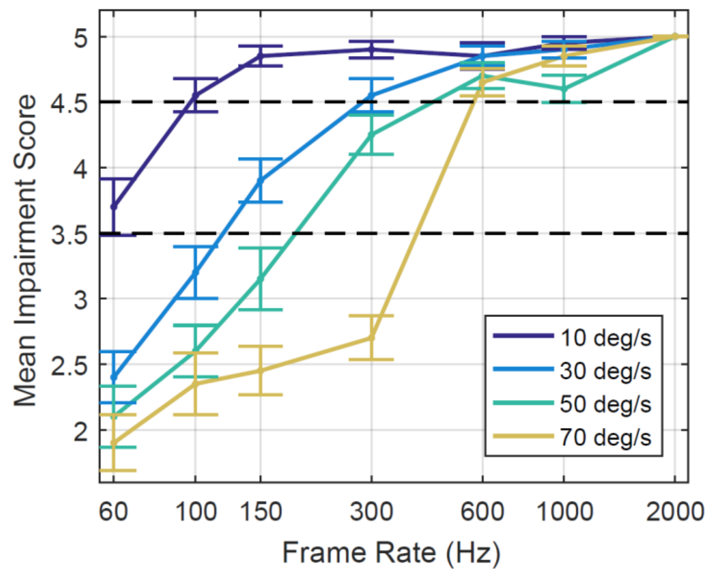
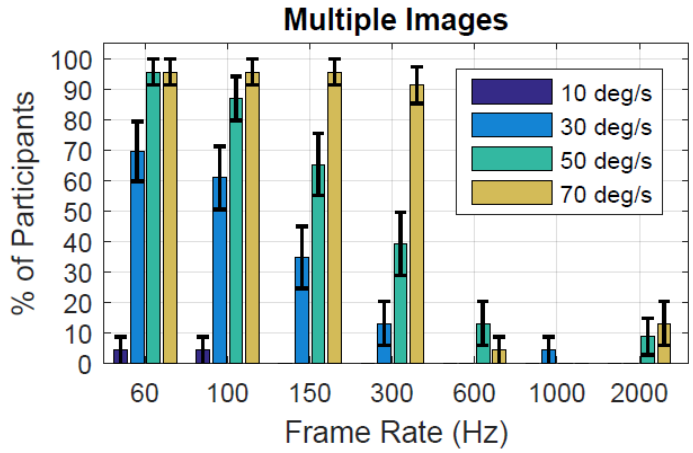
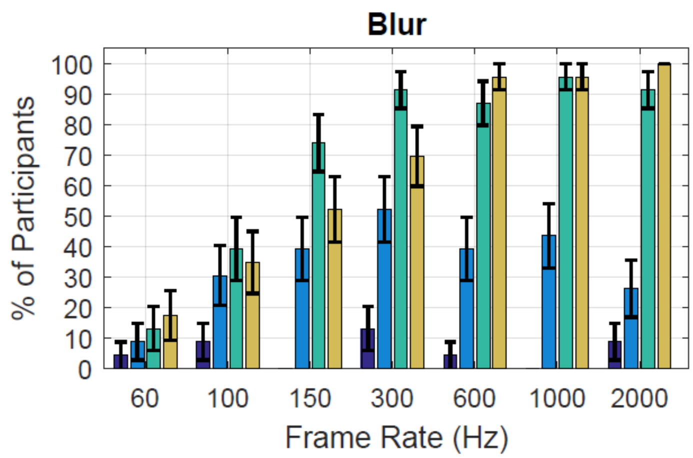


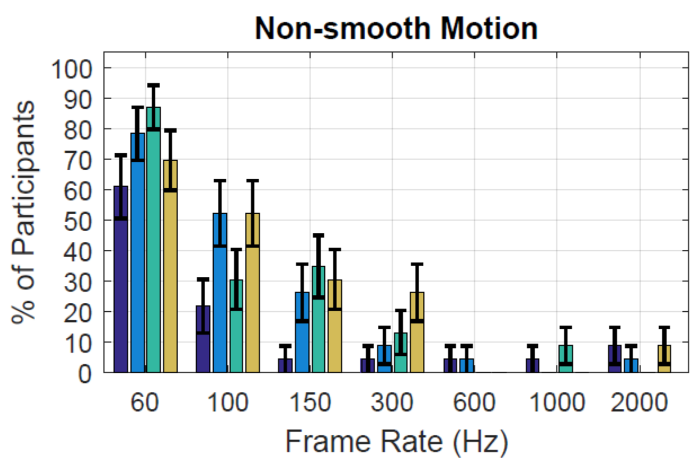
Figure 4. The mean impairment scores collected in Experiment 1. Error bars represent the standard error of the mean.



(a)



(b)



(c)

Figure 5. Percentage of participants who perceived individual motion artifacts for all test conditions. Error bars represent the standard error of the mean.

Figure 5 shows the percentage of participants who perceived individual motion artifacts over the range of tested frame rates. Non-smooth motion (Figure 5(c)) was most prominent at 60 Hz. This is the only tested frame rate below the critical flicker frequency of the human visual system[28], and as such flicker is likely to have played an important role in the perception of non-smooth motion, since an impulsive display was simulated (which minimises judder). Temporal aliasing artifacts (especially flicker) appear to be more strongly visible than any blurring imposed by the visual system[29] at the lower frame rates tested. Blur was more likely to be visible at higher speeds (Figure 5(b)).

Non-smooth motion might be expected at the higher frame rates tested, by virtue of there being a perceptible displacement between samples. We postulate that the perception of smooth (apparent) motion at these frame rates is due to the appearance of multiple images[30], and/or amodal completion[31]. This is supported by the results for multiple imaging in Figure 5(a).

In our previous work[7] we proposed that the apparent outlier in Figure 4 is due to the multiple images of the stimulus overlapping at 50˚/s when the flash rate was 150, 300 and 600 Hz. This overlapping leads to the perception of a spatial smearing, which is similar to the blurring imposed by the visual system. As such we can see an increased visibility in blur at 50˚/s compared to 70˚/s in Figure 5 for these flash rates (you would expect the visibility of blur to increase monotonically with stimulus speed[29]).

Experiments 2 & 3

Figure 6 shows the results from Experiment 2, the measured relationship between the subtended angle of the stimulus and critical frame rate. The visibility of temporal aliasing can be observed to decrease beyond a peak stimulus width of around 3.3 arc min. To ensure that all stimuli are alias-free in this case, we need to sample at around 650 Hz.

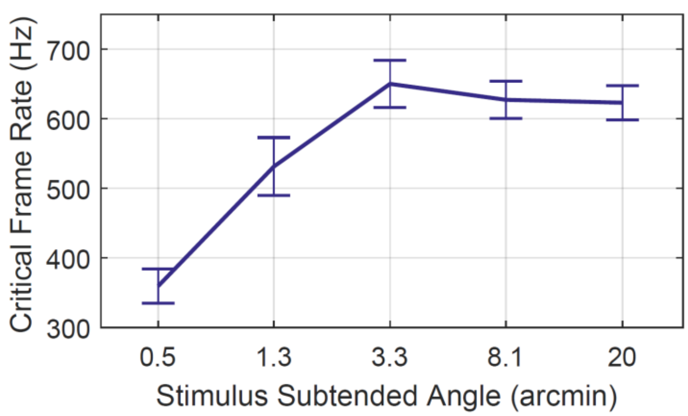


Figure 6. Results from Experiment 2 showing the relationship between the subtended angle of the stimulus and the measured critical frame rate. Error bars represent the standard error of the mean.

The Fourier transform of the (broadband) stimulus used in the experiments is calculated as:

$$F_s(u,w) = L_b\,\delta(u)\,\delta(w) - (L_b - L_s)\,W\,\mathrm{sinc}(Wu)\,\delta(ur + w) \qquad (2)$$

where *u* and *w* are spatial and temporal frequency respectively. The first term represents the spectrum of the constant background luminance, while the second term represents the spectrum of the inverted square pulse. The spectrum of spectral replicas is identical, albeit shifted temporally by multiples of the frame rate[17].

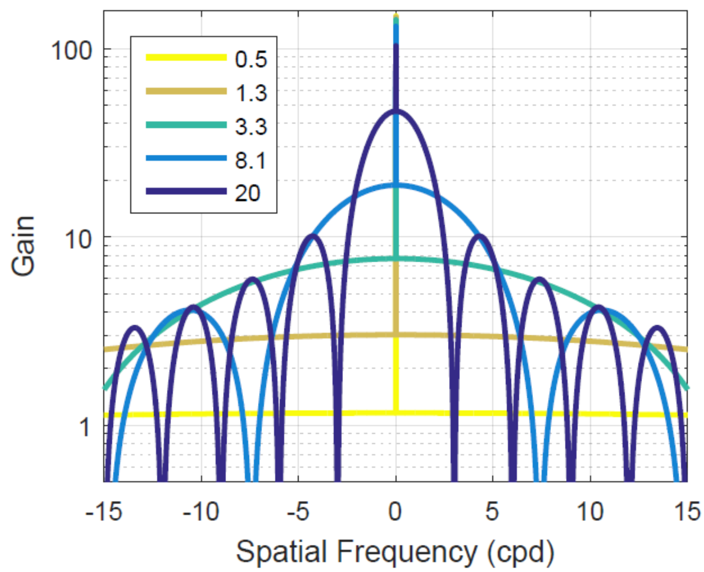


Figure 7. Spatial frequency spectrum of the stimuli used in Experiment 2.

Figure 7 shows a two-dimensional projection of $F_s(u,w)$ onto the spatial frequency axis (the magnitude of the spectrum along the thick black lines in Figure 1) for the stimulus sizes in Experiment 2. Spectral energy is concentrated at lower spatio-temporal frequencies for wider stimuli, and it is distributed across higher spatio-temporal frequencies for smaller stimuli. As a result, spectral replicas will enter the window of visibility at different locations, and therefore stimuli moving at the same speed, but with differing spectral characteristics, will have different critical frame rates (not predicted by Equation 1).

Results suggest that, if a stimulus of 3.3 arc min width can be faithfully displayed, then the critical frame rate will not be affected by increases in spatial resolution for the speed tested. This conjecture discounts any spatio-temporal filtering performed by either the camera or display.

The results from Experiment 3 are shown in Figure 8. The relationship between luminance and critical frame rate shows diminishing returns. Typical current televisions have a luminance between 150-400 cd/m^2, whereas future high-dynamic range displays may support a luminance up to 4000 cd/m^2. Our results suggest that higher frame rates will be needed in the latter case. It can be observed, for the speed tested, that the critical frame rate increases by approximately 30% when the luminance of the strobe is increased from 150 to 3200 cd/m^2.

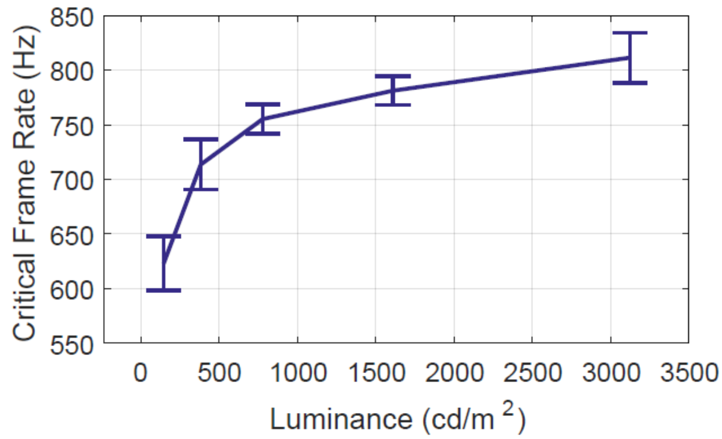


Figure 8. Results from Experiment 3, showing the relationship between luminance and the measured critical frame rate. Error bars represent the standard error of the mean.

Figure 9 shows a two-dimensional projection of $F_s(u,w)$ onto the spatial frequency axis for the different luminance levels used in Experiment 3. The gain of the signal increases with luminance, therefore spectral replicas are more likely to enter the window of visibility earlier (corresponding to higher frame rates) for the same stimulus speed. There is also an increase in size of the window of visibility with increased luminance levels[15].

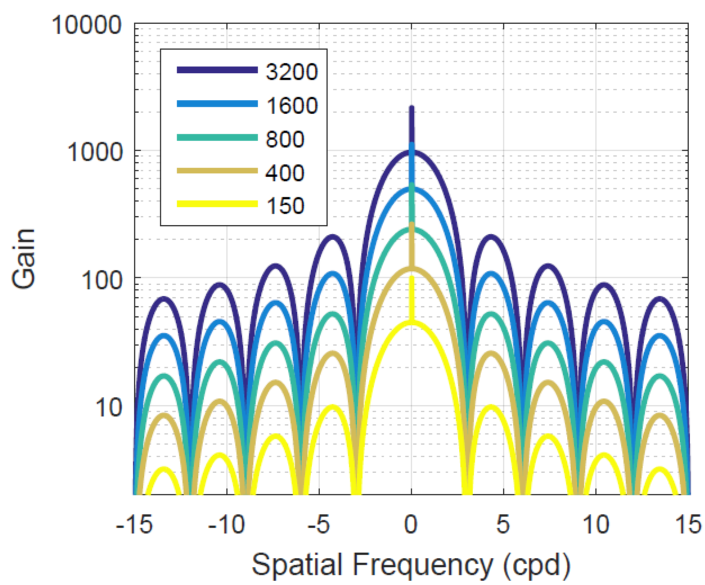


Figure 9. Spatial frequency spectrum of the stimulus for the different luminance levels used in Experiment 3.

The results from Experiments 2 and 3 show that the visibility of temporal aliasing artifacts is affected by both the size of the stimulus and luminance, demonstrating that the need for higher frame rates will be both content-dependent and dependent on the display parameters. Crucially the implication of this is that higher frame rates will be needed for future HDR formats.

Discussion

Frame rate recommendations for future video formats

Our results demonstrate that it is possible to temporally sample at frame rates lower than the critical frame rate, while maintaining an acceptable level of motion impairment. Using the results from Experiment 1 we can estimate acceptable frame rates for sample video content. Pan speeds of up to 1.3 screen widths per second have been found in ultra-high definition (UHD-1) footage of athletics shot during the Commonwealth Games 2014[32] (motion speeds will vary for other types of content).

Figure 10 demonstrates that a linear relationship exists between stimulus speed and frame rate for the data collected in Experiment 1 (this relationship has been reported previously[13,19]). By generating a model which provides a best fit for the data (in a least-squares sense), we can calculate the frame rates needed for a given screen size and viewing distance (as the speed of the stimulus subtended on the retina is dependent on these parameters).

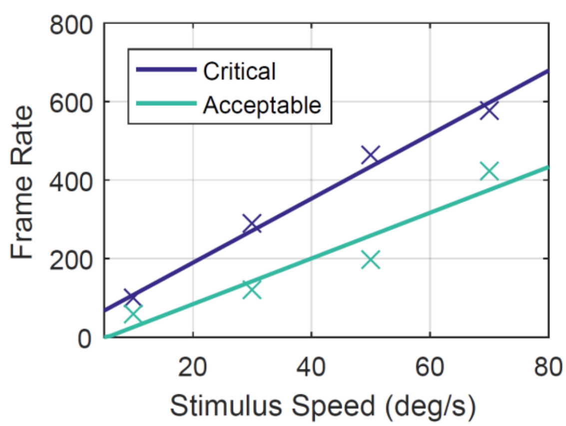


Figure 10. The relationship between stimulus speed and frame rate, from the data collected in Experiment 1.

Figure 6 demonstrates that the critical frame rate is relatively stable with respect to stimulus sizes above 3.3 arc min, so variations in the angular size due to changes in viewing distance should not be significant when assuming a large stimulus size (≥ 20 arc min).

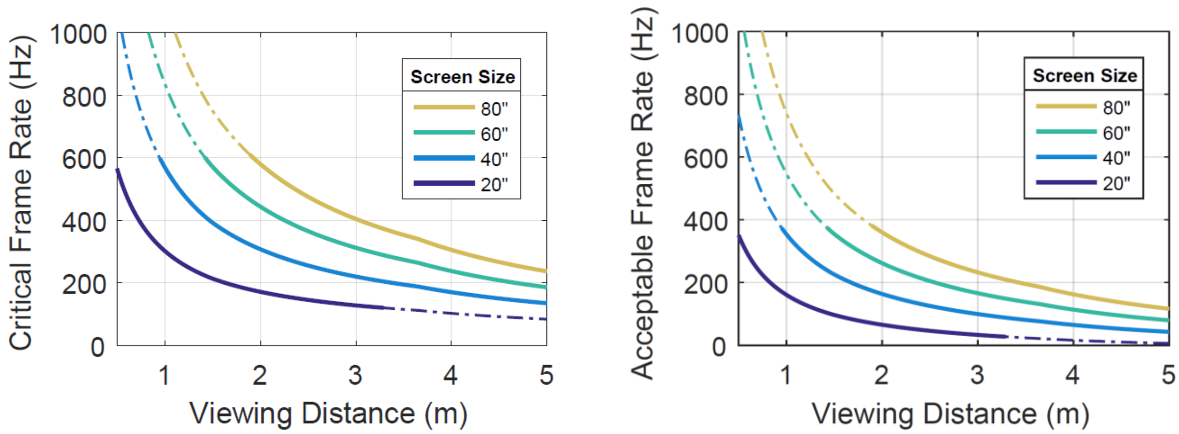


Figure 11. Example critical (left) and acceptable (right) frame rates as a function of viewing distance for a variety of screen sizes, when pan speed is 1.3 screen widths per second. The dashed portion of the curves represent where the speed is outside the range tested in the experiment, and therefore these points have been extrapolated.

Figure 11 shows the relationship between viewing distance and frame rate for a variety of screen sizes, at a pan speed of 1.3 screen widths per second, based on our experimental data. Frame rates exponentially decay with increased viewing distance, and the larger the screen size, the higher the frame rates that are required. Frame rates reported here could be up to 30% greater for the case of high-dynamic range (HDR).

Noland and Truong[34] reported that the median viewing distance and screen size for a sample of UK residents is 2.63 m and 36.6” respectively. Using our model, this corresponds to a critical frame rate of 220 Hz and an acceptable frame rate of 100 Hz, indicating that viewers would see an immediate increase in motion quality with increased frame rates compared to those commonly used (24-60Hz), without the need to change their viewing habits/environment. Noland et al. [34] also reported that the ideal screen size specified by a sample of UK residents was 48”, again using our model, this corresponds to a critical frame rate of 280 Hz and an acceptable frame rate of 140 Hz.

The authors therefore make the recommendation that for high quality video formats, frame rates should be at least 100 Hz, which would ensure acceptable motion quality for a typical viewer over a range of content types. As we move towards UHDTV formats, brighter displays and larger screen sizes, this will become increasingly important.

Practical Considerations

It is not meaningful to compare our experimental results to the critical frame rate model outlined in Equation 1, as we cannot assume that attenuation in the spectrum due to the stimulus having a finite width is negligible (Equation 2), as demonstrated in Figures 7 and 9. Watson's model[15] predicts an increase in critical frame rate for increased luminance levels, due to the window of visibility increasing in size[15,35]. However, the model does not take the size of the stimulus into account, it assumes that the stimulus is a line impulse moving a constant speed[15]. The formation of a more robust critical frame rate model, that takes into account the spectral characteristics of stimuli, is an important requirement for future work, and could be used within proposed future adaptive video formats.

There are a number of other factors that also need to be considered when investigating the visibility of temporal aliasing artifacts, such as the type of display used (e.g. impulse or hold-type). For example, a hold-type display (e.g. LCD/LED) may exacerbate the visibility of temporal aliasing artifacts, specifically non-smooth motion and edge flicker, in part due to retinal slip[36]. For the case of real video content, we must also consider the effects of both spatial and temporal masking (e.g. for static and dynamic textures), and the influence of complex and salient stimuli, as these factors will likely affect the critical frame rate, and its relationship with stimulus size and luminance.

When an actual camera shutter and a conventional display are employed, critical and acceptable frame rates lower than those indicated by our experimental results would be expected. Temporal integration by the camera shutter and display will attenuate the higher spatio-temporal frequencies in the video signal, which as a consequence will mask temporal aliasing artifacts by introducing blur for objects in motion. When choosing frame rates, blur and temporal aliasing must therefore be considered together, as they are interdependent[10].

Alongside a reduction in perceptible temporal aliasing and motion blur, there are a number of other benefits associated with higher frame rates. For example, directors have more control over the "look and feel" of the content[8], and conversion between formats is simpler (e.g. video content captured at 600 Hz can easily be converted to commonly used frame rates of 120, 60, 30, 25 and 24 Hz) [33]. There is also evidence to suggest that higher frame rates cause less stress on the viewer, highlighted by a lower blinking frequency compared to lower frame rates[37]. Kime et al.[38] have shown that higher frame rates are beneficial in a number of tasks, such as speed discrimination and digit identification.

However, a number of issues related to increased frame rates need to be addressed. These include: the relationship between frame rate and compression, the interaction between parameters in an extended video parameter space (shutter angle, spatial resolution etc.), the extent to which motion-compensated frame interpolation can mask motion artifacts, any beating with studio lighting frequencies, increased noise imposed by the camera sensor due to the inherent reduction in light in each exposure, and the role of the display type (hold or impulse).

Conclusion

In this paper we have abstracted the video acquisition process using a strobe light with controllable flash frequency. Our results show that the human visual system can tolerate some degree of impairment in motion quality due to aliasing artifacts, and that we may be able to sample at a frame rate that is 50% lower than the critical frame rate. Based on data pertaining to the median viewing distance and screen size of a sample of UK residents, and on the assumption of a maximum camera pan speed, we propose that frame rates in future immersive video formats should be greater than 100 Hz.

We have demonstrated, for the first time, the relationship between acquisition parameters such as luminance and frame rate, suggesting that higher frame rates will play a particularly important role in the visibility of motion artifacts in high dynamic range formats.

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